

Flood Hydrology Methods, including “Composite Floodplain” and “Matrix,” and Reservoir System Modeling used in the Sacramento and San Joaquin River Basins Comprehensive Study

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Abstract

In response to the destructive floods of 1983, 1986, 1995, and 1997, the U.S. Army Corps of Engineers and the Reclamation Board of the State of California are partnering a study to investigate flood damage reduction and ecosystem restoration opportunities in the Sacramento and San Joaquin River Basins, California. In this study, the hydrologic and hydraulic process for defining without-project conditions was comprised of three interrelated parts: 1) Synthetic Hydrology; 2) Reservoir Modeling; and 3) Hydraulic Modeling of floodplain areas.

This paper details the first two parts, development of baseline hydrology (45,551 mi² watershed area) and modeling of reservoir operations (73 facilities, 25.6 MAF gross pool storage), needed to support ongoing system analyses. Discussion emphasizes conceptual relations between flood hydrology and floodplain delineation, a short retrospective of Central Valley flood events, a method for developing synthetic flood hydrographs, and system-wide reservoir modeling. Conclusions are drawn regarding the effective use of gaged flow data in flood frequency analyses, benefits of performing flood frequency analyses from a watershed perspective, the influence of reservoirs in flood hydrology, and potential of Comprehensive Study methodologies for use in other studies.

Abstract and paper are adapted from recent ASCE articles: 1) Hickey, J. T., Collins, R. F., High, J. M., Richardson, K. A., White, L. L., and Pugner, P. E. (2002). “Synthetic rain flood hydrology for the Sacramento and San Joaquin River Basins.” *Journal of Hydrologic Engineering*, 7, 195-208; and 2) Hickey, J. T., Bond, M. V., Patton, T. K., Richardson, K. A., and Pugner, P. E. (In Press). “Reservoir Simulations of Synthetic Rain Floods for the Sacramento and San Joaquin River Basins.” *Journal of Water Resources Planning and Management*.

Introduction

Central Valley flooding of January 1997 was one of the most costly and extensive flood disasters in California’s history. Existing flood damage reduction systems were stressed to capacity and beyond (USACE and Rec Board 1999). After the event, an action team convened by then California Governor Pete Wilson recommended that the State Legislature authorize the Reclamation Board of California to sponsor and support the U.S. Army

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Corps of Engineers (USACE) in developing new master plans for flood damage reduction in the Central Valley. This suggestion was endorsed by the State and in 1998 (U.S. Congress 1998), USACE received federal authorization to develop a comprehensive plan for flood damage reduction and ecosystem restoration. This effort has since come to be known as the Sacramento and San Joaquin River Basins Comprehensive Study and focuses on formulating improvements to, and integrating ecosystem restoration with, the existing flood damage reduction system.

An important step in planning studies is establishing “without-project conditions.” This step defines the system that exists or will exist before any possible improvements proposed by a study are implemented and thereby provides a frame of reference for assessing alternatives to that system.

In the Comprehensive Study, the hydrologic and hydraulic process for defining without-project conditions was comprised of three interrelated parts: 1) Synthetic Hydrology, 2) Reservoir Modeling, and 3) Hydraulic Modeling of floodplain areas. This paper details the first two parts, development of baseline hydrology and modeling of reservoir operations, needed to support ongoing system analyses.

Synthetic hydrology focused on development of 50%, 10%, 4%, 2%, 1%, 0.5%, and 0.2% exceedance (2-, 10-, 25-, 50-, 100-, 200-, and 500-yr) flood events for an exceptionally large (45,551 mi²) watershed area. Discussion of this work includes 1) updated natural flow frequency curves for locations within the basins; 2) a retrospective of historic floods that have impacted Central Valley rivers and the synthetic storm centerings developed for the percent exceedance flood events; and 3) construction of flood hydrographs. For more information regarding Study background and Synthetic Hydrology, readers are directed to Hickey et al. 2002.

The reservoir simulation software selected for use was *HEC-5: Simulation of Flood Control and Conservation Systems* (USACE 1998). Calibrated reservoir models were used to simulate the 50%, 10%, 4%, 2%, 1%, 0.5%, and 0.2% exceedance flood events prepared in the Synthetic Hydrology. Reservoir model results were later input to hydraulic models, which delineated floodplain areas and defined stage-frequency relationships needed to estimate expected annual flood damage in the lower basins of the Sacramento and San Joaquin drainages. This entire process, from hydrology to economics, characterized the without-project conditions needed for plan formulation. Full reports (USACE and Rec Board 2000) are available via the web at <http://www.compstudy.org>.

Study Area

The Central Valley of California was once a series of rivers, lakes, and wetlands. Changing with the seasons, all were components in a diverse and productive ecosystem. Now home to the Central Valley Project (the largest U.S. Bureau of Reclamation project), the State Water Project (the largest state-built water project in the U.S.), and numerous other irrigation and utility reservoir and conveyance systems, the Central Valley is composed more of canals, reservoirs, and farm lands and has one of the most heavily regulated water systems in the world.

The Comprehensive Study area encompasses the watersheds of the two major river systems of the Central Valley, the Sacramento River in the north and the San Joaquin River in the south (figure 1). These rivers have a combined drainage area of 45,551 mi², an area slightly larger than the state of Pennsylvania.

Figure 1: Map of the Sacramento and San Joaquin River Basins Comprehensive Study area. Circles M1-M8 highlight mainstem points where flow series are computed by routing and summing flows from upstream tributary locations. All circled points are described in table 1. Watershed areas above 6,000 ft are highlighted. **California**

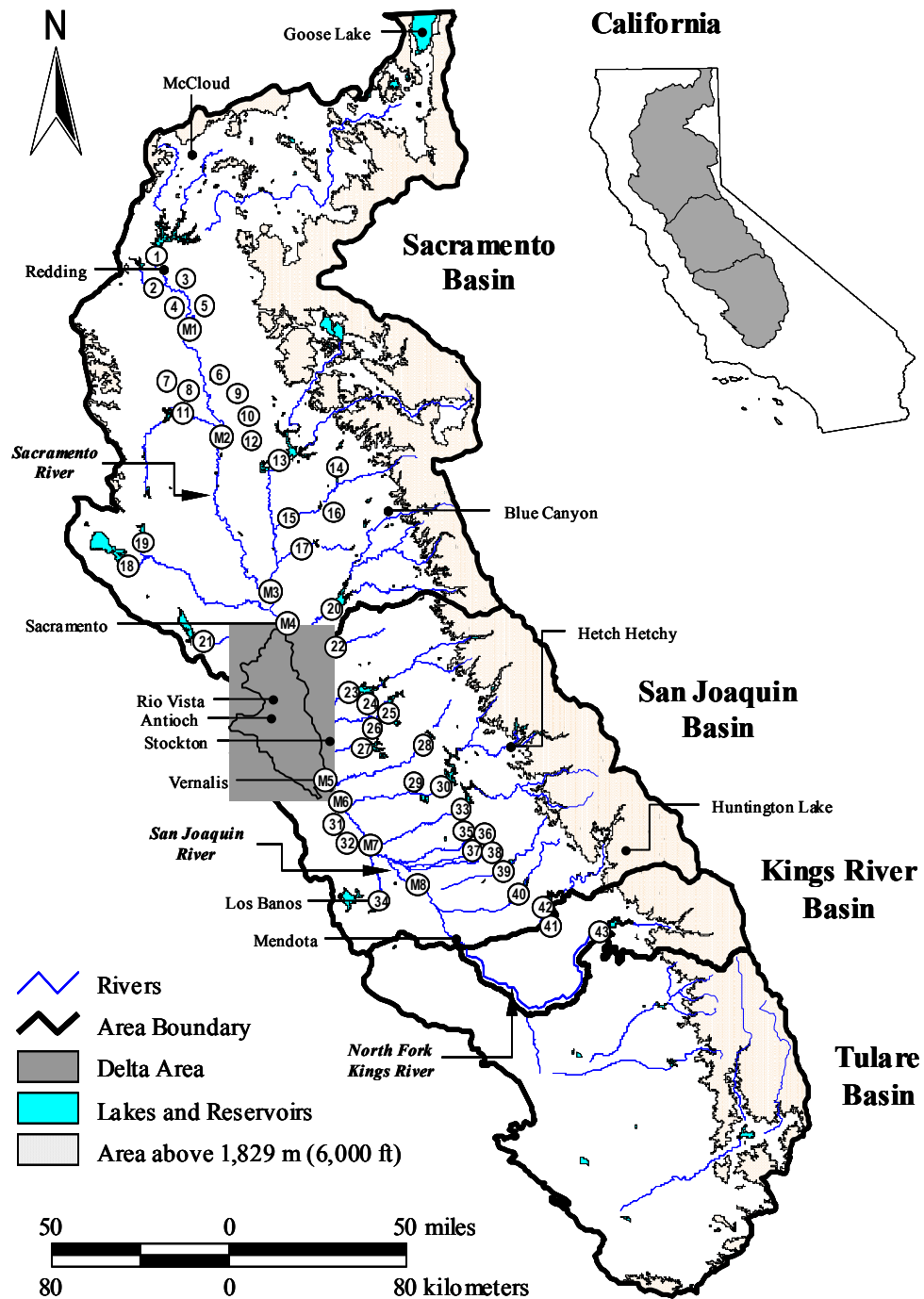


Table 1: Drainage areas and average annual yields for select Central Valley locations. Mainstem locations are identified by an alphanumeric of “M#”. Data at mainstem points are computed by routing and summing flows from upstream tributary locations.

<u>Location ID</u>	<u>Tributary Locations</u>	<u>Drainage Area</u> <u>mi²</u>	<u>Average Annual Yield</u> <u>1000 ac-ft</u>
1	Sacramento River at Shasta Dam	6,421	5,696.0
2	Clear Creek near Igo	228	342.4
3	Cow Creek near Millville	927	488.5
4	Cottonwood Creek near Cottonwood	425	642.1
5	Battle Creek below Coleman Fish Hatchery	357	349.5
M1	Sac River at Bend Bridge	8,900	8,486.3
6	Mill Creek near Los Molinos	131	227.6
7	Elder Creek near Paskenta	92	72.9
8	Thomes Creek at Paskenta	203	209.9
9	Deer Creek near Vina	208	235.4
10	Big Chico Creek near Chico	72	105.6
11	Stony Creek at Black Butte	740	495.8
M2	Sac River at Ord Ferry (Latitude)	12,050	9,896.2
12	Butte Creek near Chico	147	299.2
13	Feather River at Oroville	3,624	4,294.2
14	Yuba River at New Bullards Bar	489	1,299.9
15	Yuba River at Marysville	1,339	1,816.2
16	Deer Creek near Smartville	85	110.1
17	Bear River near Wheatland	292	337.1
M3	Sac River at Verona (Latitude)	21,251	17,290.1
18	Cache Creek at Clear Lake	528	282.6
19	NF Cache Creek at Indian Valley	121	114.3
20	American River at Fair Oaks	1,888	2,750.4
M4	Sac River at Sacramento (Latitude)	26,150	20,679.3
21	Putah Creek at Berryessa	566	386.3
22	Cosumnes River at Michigan Bar	536	364.4
23	Mokelumne River at Camanche	677	1,162.4
24	Cosgrove Creek near New Hogan	21	5.9
25	Calaveras River at New Hogan	363	181.5
26	Duck Creek at Duck Creek gage	8	1.8
27	Littlejohn Creek at Farmington	212	56.2
M5	SJQ River at Vernalis (Latitude)	13,536	7,616.0
28	Stanislaus River at New Melones	904	1,175.0
M6	SJQ River at Maze Road Bridge (Latitude)	12,400	6,422.7
29	Dry Creek near Modesto	192	74.0
30	Tuolumne River at Don Pedro	1,533	1,918.5
31	Del Puerto Creek near Patterson	73	5.5
32	Orestimba Creek near Newman	134	13.4
M7	SJQ River at Newman (Latitude)	9,520	4,478.1
33	Merced River at Exchequer	1,037	1,061.0
34	Los Banos Creek at LB Dam	159	11.9
35	Burns Creek at Burns	74	22.1
36	Bear Creek at Bear	72	20.6
37	Owens Creek at Owens	16	7.4
38	Mariposa Creek at Mariposa	107	36.2
M8	SJQ River at El Nido (Latitude)	6,900	3,319.6
39	Chowchilla River at Buchanan	235	85.8
40	Fresno River at Hidden	234	96.4
41	Big Dry Creek at BDC Dam	82	9.0
42	San Joaquin River at Friant	1,676	1,788.7
43	Kings River at Pine Flat	1,542	1,728.7

The climate in the Central Valley is temperate and varies according to elevation. In valley floor and foothill areas, summers are hot and dry and winters are cool and moist. At higher elevations the summers are warm and slightly moist and the winters are cold and wet.

Flows in both watersheds are generated by a series of major and minor tributaries, all of which ultimately drain to the Sacramento and San Joaquin River Delta. Large tributary rivers form in the mountains and flow onto the relatively flat valley floor, a combination that makes flooding a frequent and natural event in the Central Valley. Table 1 presents average annual yields for Central Valley tributaries at locations noted on figure 1. To counter seasonal and geographic trends in precipitation, runoff, and water demand, numerous reservoirs were constructed to provide recreation, hydropower, flood damage reduction, and water supplies for environmental management, growing municipalities, and an agriculture industry that generates tens of billions of dollars per year.

Floodplain Background

Before entering into a discussion of methodology details, it is important that the reader clearly understand the ultimate goal of this effort, which is to prepare storm centerings and flood hydrographs that feed reservoir and hydraulic models, whose simulations culminate in delineation of Central Valley floodplains. Recognition that this hydrology shapes floodplains is a critical concept, considering the complexity of floodplains in large spatial areas with numerous contributing tributaries. While it is intuitive that flows create floodplains, more is involved than at first appears.

Composite Floodplain

The “Composite Floodplain” concept is realized when one understands that a frequency floodplain is not created by a single flood event, but by a combination of several events, each of which shapes the floodplain at different locations (figure 2). In addition, as one moves downstream in a watershed, the Composite Floodplain becomes increasingly complex, because with the confluence of each additional tributary, the number of possible scenarios that could shape the floodplain grows. The role of tributaries in shaping floodplains individually and as a system is the foundation of the Composite Floodplain concept and a cornerstone of the Synthetic Hydrology Analysis. It is a theme that guides the methodology and is discussed throughout this report.

The stretch of Tuolumne River between New Don Pedro Dam and Reservoir and its confluence with the San Joaquin River near Maze Road Bridge (figure 1, site 30 to M6) provides an example of this concept. Don Pedro Reservoir is a flood damage reduction project that regulates flows from the upper basin of the Tuolumne. Directly below the reservoir, the 1% floodplain is shaped by a 1% inflow to Don Pedro, the existing operational criteria for that facility, and the channel shape below the dam. The combined influence of these factors continues until the Tuolumne courses through the City of Modesto and joins with flows from Dry Creek (figure 1, site 29). At this point, the floodplain becomes two-pronged with inundated areas extending up both Dry Creek and the Tuolumne River. Here, the shape of the floodplain is a function of the timing and magnitude of flow from two tributaries,

hydraulic (including backwater) influences of each upon the other, and channel and inundated landforms. This changes again when the Tuolumne comes within the realm of influence of the San Joaquin River mainstem and, thereby, the twelve other tributaries that join the mainstem above Maze Road.

Ultimately, the 1% floodplain in the Lower Tuolumne may not be shaped by the 1% outflow from Don Pedro. A different storm scenario may generate flows on the San Joaquin mainstem that create larger extents of inundation (despite a lower return period event on the Tuolumne) through backwater effects or by simply introducing large out-of-channel flows to floodplain areas. Methodology for the Comprehensive Study was developed to ensure that such characteristics are reflected and that the Composite Floodplain represent the extent of inundation possible at all locations for any given percent exceedance.

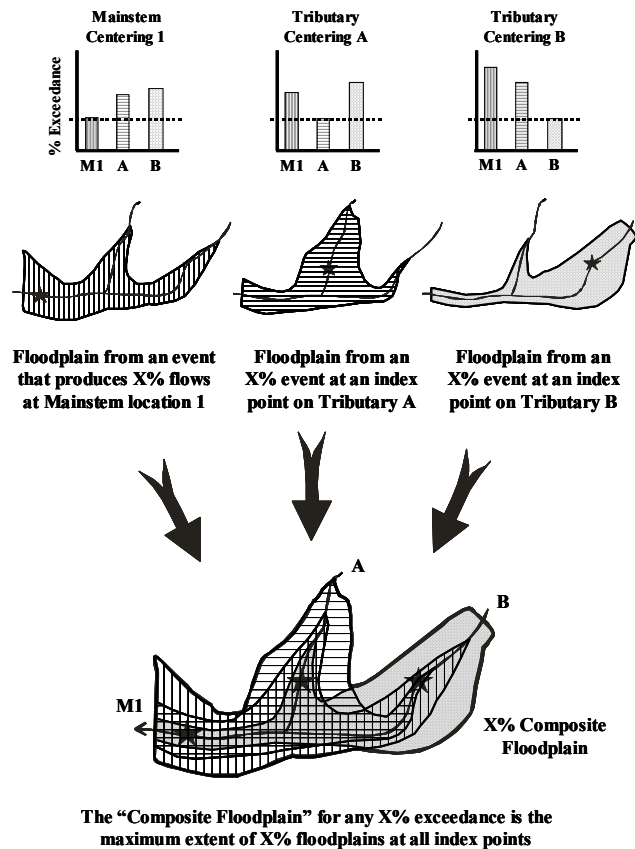


Figure 2: The "Composite Floodplain" defines the extent of inundation possible at all locations for any given percent exceedance. In this study, two centering types (mainstem and tributary) were used to shape frequency floodplains. Dashed line in bar graphs represents the target % exceedance. Percent exceedance is inversely proportional to flood intensity (taller bars indicate weaker intensities).

Methodology and Discussion

The Synthetic Hydrology Analysis investigated three fundamental subjects during the formulation of synthetic flood events: 1) the amount of runoff produced during a percent exceedance flood; 2) the contribution of individual tributaries to this total volume; and 3) translating these flood volumes and distributions to hourly time series ready to feed into reservoir simulations models.

Development of Natural Flow Data and Unregulated Frequency Curves

Preparation of unregulated frequency curves was an integral step in the first of the three study subjects and was undertaken at mainstem and tributary locations. Unregulated frequency curves plot historic points and statistical distributions of unimpaired flows (no reservoir influence). Each curve displays volumes or average flow rates for a different time duration over a range of % exceedances. Essentially, these can be used to translate: 1) hydrographs to frequencies and 2) frequencies to flood volumes. After a curve is developed, the runoff volume for any percent exceedance flood can be obtained from the plot for that curve's specific location.

Curves were constructed using moving averages of the daily flow series for 3-, 5-, 7-, 10-, 15-, and 30-day durations at all points of interest. Wintertime maxima were picked from the series of averages for each water year. All snowmelt-driven events were screened out from these duration peaks through visual inspection (rainfall and snowmelt hydrographs convey volume in noticeably different shapes); screened events were replaced with the highest rainflood, or rainfall driven, flows experienced during that water year.

Values were sorted, ranked, and graphed with median plotting positions. Statistics were computed for these samples of annual floods with USACE statistical analysis tools (USACE 1972; USACE 1992). Sample mean, standard deviation, and skew were computed and, in some cases, smoothed to better represent the values for each duration. Final statistics were used to construct best-fit curves with log Pearson Type III distributions in a manner consistent with current guidelines (Hydrology Subcommittee 1982).

Development of the unregulated frequency curves for the tributaries required daily natural flow data for all target locations. Natural flow data from tributaries were routed to downstream locations for use in constructing mainstem “index” frequency curves.

Unregulated frequency curves were prepared for 43 tributary locations. Index curves were constructed for 8 mainstem locations (table 1). For any location, the amount of runoff volume anticipated during any percent exceedance flood can be read off of the family of best-fit curves or computed directly from the final statistical distribution of each duration.

Flood volumes at index curve (mainstem) locations represent the sum of volumes contributed by all upstream tributaries, but do not offer any information regarding how each provides to the whole. In this sense, these index curves provide frequency-based targets, in terms of volumes, at mainstem locations for synthetic flood patterns that involve a number of upstream tributaries.

The approach formulated and described above was driven entirely by historic flow data. Each year of record included the influence of snowmelt, infiltration, interception, precipitation distribution, timing of runoff, storm construct, and physical basin attributes for that annual rainflood event. Historic flow data records provided a sufficient sample of flood events to characterize synthetic flood volumes and tributary-system relationships.

No synthetic precipitation events were required. In fact, precipitation never entered into any portion of the methodology.

Historic and Synthetic Storm Centerings

With the completion of the natural flow data analysis and compilation of the 51 curve sets (43 tributary and 8 mainstem), amounts of flood volume at discrete locations within the basins were quantified. At mainstem locations, total volumes reflected the combined flows of between 5 and 20 individual tributaries (depending on location). To perform simulations with the reservoir and hydraulic models, this total volume needed to be redistributed into the system of tributaries through a storm pattern.

In nature, storms trigger high flows on isolated tributaries and large-scale river systems as a function of storm structure, air temperature, water content, storm path, snow pack, orographic influence, basin alignment, and a

host of other geophysical and meteorological variables. Each storm is unique, but certain dynamics tend to be common to a variety of storm types, especially those that trigger productive (in terms of volume) events within the Central Valley. Development of patterns is possible through a number of methods, including random generation, use of a singular historic event, and uniform or ramped concurrencies.

The most realistic patterns for synthetic floods are formulated based on historic storms. A detailed analysis of several events was undertaken to identify storm trends and distributions that could be incorporated into generalized patterns.

Retrospective of Historic Flood Events in the Central Valley. Nineteen historic flood events were analyzed. These 19-events include storms that were focused on individual tributaries as well as those that had a powerful system-wide effect.

For each year, a time window was set that contained the storm event and some additional time to allow the storm pattern to complete its influence throughout the basin. Duration flows (1-, 3-, 7-, 15-, and 30-day average flows) within this event window were analyzed for all significant tributaries and several mainstem locations. These flows were translated to return periods based on the unregulated flow and index frequency curves developed during the natural flow analysis.

By comparing return periods instead of flow rates, the distribution of storm patterns is normalized spatially; return periods are a consistent measure of intensity from basin to basin, while flow rates, as a function of drainage area, alignment, and other factors are tributary-specific. Investigating return periods clarifies patterns, in terms of how individual storms impacted a system of tributaries. In this case, return periods were investigated in lieu of percent exceedances because return periods are proportional to intensity, which made it easier to visualize fluctuating intensities (% exceedance is inversely proportional, i.e., the lower the percentage the higher the flows). Considering multiple storm events highlights trends linking tributary responses, which can be used to guide development of generalized storm patterns.

Looking into the Matrix. All return periods, locations of interest, flood durations, and year of event were tabulated into Sacramento and San Joaquin Basin storm matrices referred to jointly as the Matrix (table 2 shows an excerpt of the full Matrix).

The Matrix is a valuable product of this study. Nineteen flood events compared for all major tributaries in a complex hydrologic system. Laid out upstream to downstream, storm and tributary dynamics can be looked at in diverse permutations of flood durations, storm combinations, and tributary sets.

Matrix investigations pointed to several trends that were eventually incorporated into synthetic storm centerings. Among the first dynamics noticed was the presence of spatial trends and storm “bull’s eyes” within individual storm events. “Bull’s eyes” were created as historic storms impacted certain spatial areas with greater intensity than surrounding areas. Nearly all events in the Matrix displayed some sort of spatial trend or bias towards a specific area. The floods of February 1986, for example, were most intense over the mid-latitudes of the Central Valley, including the lower Sacramento Basin (Feather, Yuba, Bear, and American Rivers), Delta (Mokelumne and Cosumnes Rivers), and Lower San Joaquin Rivers (Stanislaus River).

Table 2: Excerpt from the Sacramento and San Joaquin River Basins historical flood Matrix (9 of 19 storms analyzed are included). Table contains return periods (in years) for the highest 1-day unimpaired flow during discrete storm event windows. Values do not necessarily reflect the maximum flow experienced in the water year containing the event window. Locations 1-11 are listed north to south in groups of east and westside basins. The storm in 1974 was distinctly northern and not analyzed for San Joaquin River tributaries. Similar tables for the 3-, 7-, 15-, and 30-day durations are available in USACE and Rec Board 2000.

WATER YEAR CONTAINING STORM EVENT WINDOW										
ID	Location	1997	1995	1986	1983	1982	1974	1967	1956	1951
1	Sacramento River at Shasta	133	6	13	5	2	103	2	18	1
2	Clear Creek near Igo	20	5	4	27	1	40	2	10	1
4	Cottonwood Creek near Cottonwood	8	5	13	20	1	45	1	12	1
3	Cow Creek near Millville	4	2	10	7	1	14	1	2	1
5	Battle Creek below Coleman Fish Hatchery	100	5	9	8	3	48	1	4	1
M1	Sac River at Bend Bridge	67	5	13	12	1	69	1	15	1
6	Mill Creek near Los Molinos	88	5	16	4	3	12	2	9	1
9	Deer Creek near Vina	174	7	23	7	5	10	1	13	1
10	Big Chico Creek near Chico	140	21	19	5	6	4	2	6	1
7	Elder Creek near Paskenta	7	9	14	15	1	14	1	5	1
8	Thomes Creek at Paskenta	5	8	68	3	1	33	1	20	1
11	Stony Creek at Black Butte	9	8	15	10	2	8	1	7	1
M2	Sac River at Ord Ferry (latitude)	40	22	22	13	2	29	2	17	1
12	Butte Creek near Chico	>100	5	26	4	5	4	2	16	2
13	Feather River at Oroville	105	10	33	3	5	4	1	20	3
14	North Yuba River at New Bullards Bar	55	4	35	2	5	3	1	37	5
17	Bear River near Wheatland	31	4	74	2	2	2	2	9	5
M3	Sac River at Verona (latitude)	87	8	57	6	4	8	2	40	3
18	Cache Creek at Clear Lake	73	7	14	10	3	5	1	10	1
20	American River at Fair Oaks	78	5	29	2	5	3	1	37	16
M4	Sac River at Sacramento (latitude)	95	8	66	5	4	7	2	38	4
22	Cosumnes River at Michigan Bar	210	7	31	7	4		1	24	6
23	Mokelumne River at Camanche	152	6	18	5	15		2	27	22
25	Calaveras River near New Hogan	10	4	27	4	4		2	4	2
27	Littlejohn Creek at Farmington	7	3	12	4	2		2	9	
M5	SJR River at Vernalis (latitude)	89	13	35	6	12		4	58	25
28	Stanislaus River at New Melones	54	8	19	3	11		3	68	35
M6	SJR River at Maze Road Bridge (latitude)	89	16	32	7	13		4	54	19
29	Dry Creek near Modesto	6	16	6	3	12		2	81	1
30	Tuolumne River at Don Pedro	83	10	12	4	12		5	79	20
32	Orestimba Creek near Newman	5	14	8	7	4		2	9	2
M7	SJR River at Newman (latitude)	38	14	23	8	11		5	51	13
33	Merced River at Exchequer	49	15	11	5	16		4	63	22
36	Bear Creek at Bear	6	6	3	5	3		3	36	4
M8	SJR River at El Nido (latitude)	71	19	30	8	19		9	66	10
39	Chowchilla River at Buchanan	12	12	9	8	4		4	182	7
40	Fresno River at Hidden	16	19	10	9	10		6	28	8
41	Big Dry Creek at BDC Dam	10	29	19	7	33		2	19	1
42	San Joaquin River at Friant	61	16	12	4	4		18	57	18
43	Kings River at Pine Flat	34	11	10	3	35		59	76	36

Mainstem locations below these “bull’s eyes” experienced lower return periods, because here the intensity of flooding is a function of all upstream tributaries, not just those which were especially intense. In this sense, the mainstem acts as a buffer which absorbs and moderates localized extremes because they alone do not add enough volume to the system to maintain the high return period.

A key finding was that orographic effects were most pronounced in the rarest events. The January 1997 floods were the highest on record in the San Joaquin Basin. In this event, as well as 1982, 1967, 1951 and, to a lesser extent, 1986 and 1956, return periods were consistently more extreme in the higher elevation San Joaquin basins than in the foothill tributaries. This relationship highlights the effects of the high Sierra mountain range in the San Joaquin and Tulare Basins.

Orographic effects in the Sacramento Basin were definitely visible, but not as well defined as those in the San Joaquin. Still, higher basins in the floods of 1974 and 1956, and to a lesser extent in 1997 and 1986, displayed distinctively more extreme return periods than the lower basins. It is likely that the more pronounced orographic influence in the southern Central Valley is related to the average ridge crest elevation along the Sierras, which is generally lower in the Sacramento Basin than in the San Joaquin and Tulare, but this remains uncertain.

The years cited above for both the Sacramento and San Joaquin Basins basically comprise a subset of the Matrix containing the most severe historical events analyzed in this study. For storms that were generally less intense, orographic effects were muted at best and basically not visible. Storms tended to become more and more evenly distributed until any dynamics that could potentially be tied to orographics were just as likely attributed to random noise.

The Matrix also points out that natural dynamics are highly variable. Storm cells nested within the larger storm structure are powerful and have the ability to trigger individual tributaries significantly (i.e., the 1986 flood on the Bear River). Even with the supporting evidence for orographic influence, there are Matrix examples of storms that demonstrate a consistently opposite bias; in the San Joaquin Basin during the March 1995 floods and in the Sacramento Basin during the 1983 floods, return periods for foothill tributaries exceeded those of neighboring higher basins.

Synthetic Storm Centering Development for X% Exceedance Flood Events. Based on trends identified in the historic storm analysis and in keeping with the concept of the Composite Floodplain, guidelines for centering development were formulated and synthetic storm centerings were constructed.

In the context of this study, a storm centering is defined simply as a set of percent exceedances assigned to a set of tributaries. Centerings were developed separately for the Sacramento and San Joaquin Basins. Each tributary was included in all centerings within its basin.

Two basic types of storm centerings were analyzed (figure 2). The first consists of basin-wide storm events (mainstem centerings), which are significant on a regional basis and produce large runoff volumes throughout the system. The second are tributary specific storms (tributary centerings), which generate extremely large floods on individual rivers, but are not widespread enough to produce the runoff volumes typical of basin-wide events.

Due to the differences in storm character, mainstem and tributary centerings needed to be addressed with separate sets of governing guidelines. There are similarities between rule sets, but in general, approaches are dissimilar.

Mainstem centerings designed to stress widespread valley areas. Index frequency curves provide the hypothetical volumes that the basin will produce during X% exceedance flood events. The role of the mainstem centerings is to distribute these volumes back into the basin, tributary by tributary, in accordance with patterns

visible in historic storm events. Once the volume is distributed it will be translated into hydrographs and routed through reservoir simulation models to produce the X% regulated hydrographs needed to construct floodplains throughout the system.

Mainstem centerings reflect a generalized storm pattern based on a number of historic events. Through the incorporation of multiple floods into one characteristic pattern, relationships between tributaries become more stable and the influences of powerful, but isolated, storm cells are downplayed.

Characteristic patterns were developed for each mainstem location. Where available, historic events that displayed flood “bull’s eyes” in the watershed above the mainstem location of interest were used to formulate synthetic patterns. The orographic effects noted in the Matrix analysis were also incorporated, especially for the rarest X% events. To assure that patterns were developed consistently, guidelines for mainstem pattern construction were formulated and are presented in table 3.

Tributary centerings designed to stress individual tributary systems. Whereas mainstem centerings were formulated as spatially distributed events that were productive on a system-wide basis, tributary centerings were designed to simulate extreme floods on individual rivers generated by storm systems that were not widespread enough to produce runoff volumes typical of basin-wide events. In this sense, tributary centerings seek to reflect the powerful and isolated storm cells intentionally downplayed by the mainstem centerings.

Preparation of tributary centerings (table 4) was more straightforward than those for the mainstem, because in any tributary centering, the % exceedance of the target tributary was set equal to the desired X% exceedance (i.e., the 1% centering for the Tuolumne River includes a 1% inflow to Don Pedro Reservoir). All other tributaries experience a higher % exceedance. Intertributary relationships were defined using patterns visible in the Matrix.

Table 3: Guidelines for preparation of mainstem centerings.

- 1) All mainstem centerings must be supported by patterns visible in historic storms.
- 2) Flood volumes produced by a mainstem centering must be roughly equal to the volumes specified by the index frequency curves.
- 3) The % exceedance of any individual tributary must exceed that of the mainstem centering being developed.
- 4) Orographic effects are most pronounced in the rarest events.
 - a) Basins higher in elevation experience less frequent events than low elevation basins for 1%, 0.5%, and 0.2% mainstem centerings.
 - b) In 4% and 2% events, orographic effects are less pronounced and mainstem centerings begin to reflect a more evenly distributed pattern.
 - c) In 50% and 10% events, mainstem centerings reflect an evenly distributed pattern.
- 5) As an individual tributary becomes more distant from the mainstem location of interest, the % exceedance of that tributary is increased.
 - a) This relationship is maintained within the context of the fourth rule.

Table 4: Guidelines for preparation of tributary centerings.

- 1) All tributary centerings must be supported by patterns visible in historic storms.
 - a) Generic patterns not supported by the historic storm analysis may need to be applied to tributaries which have not been the focal basin in any of the 19 historic events.
- 2) The % exceedance of the target tributary is always set equal to the desired % exceedance.
- 3) No other tributary can have a % exceedance as low as that specified for the target tributary.
 - a) Percent exceedances for adjacent tributaries are increased by the highest rate visible in historic storm patterns. This maximum rate defines the relationship between those tributaries as the target tributary moves further and further away.
 - b) Tributary % exceedances are increased in this manner until reaching a baseline percentage, which is a function of the target % exceedance, or until the tributary is distant enough from the target tributary to have no possible influence on that tributary’s floodplain, at which point it would be also be increased to the baseline percentage.

Construction of flood hydrographs

To this point, the discussion has focused primarily on flood frequencies, not on flood flows. The final topic in the Synthetic Hydrology Methodology is the translation of frequencies to hourly flood hydrographs for use in reservoir simulations and hydraulic modeling (USACE and Rec Board 2000). The translation process (figure 3) involved 3 steps: 1) obtain the average flood flow rates from the unregulated frequency curves; 2) separate these average flows into wave volumes; and 3) distribute volumes into a wave series. This process was performed only at the tributary locations. Mainstem flood hydrographs always resulted from the routed contributions of upstream tributaries.

Translation of frequencies to hourly flood hydrographs was automated within a spreadsheet. In fact, the entire process was mechanized to the point where generation of the 30-day hourly series was entirely driven by entering the % exceedances of the tributaries within each centering into the spreadsheet. Hydrographs were automatically computed and then copied into text files for entry into the Hydrologic Engineering Center's Data Storage System, HEC-DSS, which is the database used by HEC-5.

Reservoir System Modeling

HEC-5, a computer program first developed and distributed in 1973, was designed by the Hydrologic Engineering Center (HEC) to offer guidance in real-time reservoir release decisions and to aid in planning studies for proposed reservoirs, operation alternatives, and flood space allocation. HEC-5 reservoir models (figure 4) were developed, calibrated, and used to simulate the 50%, 10%, 4%, 2%, 1%, 0.5%, and 0.2% exceedance flood events prepared in the Synthetic Hydrology. Reservoir model results were later input to hydraulic models, which delineated floodplain areas and defined stage-frequency relationships needed to estimate expected annual flood damage in the lower basins of the Sacramento and San Joaquin drainages.

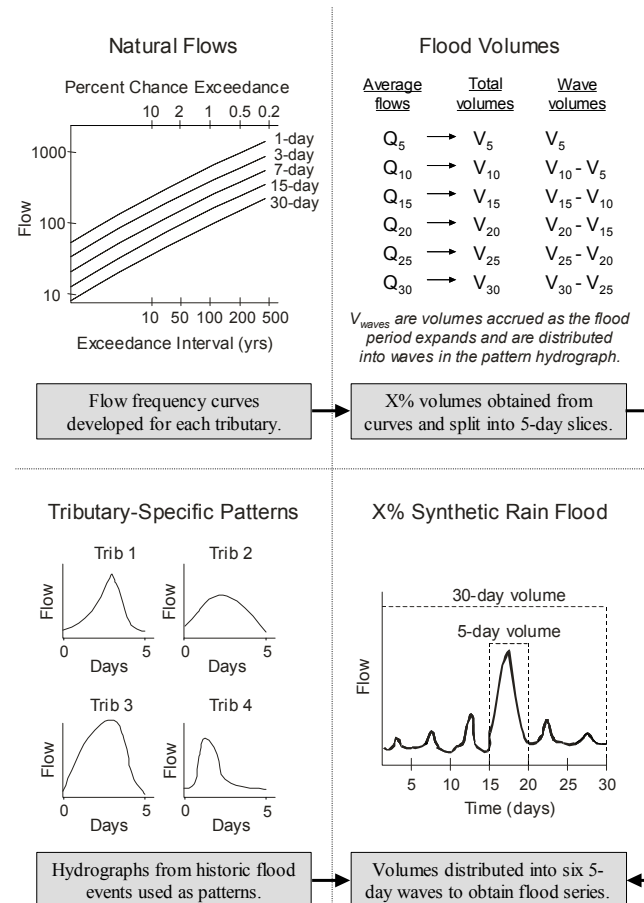
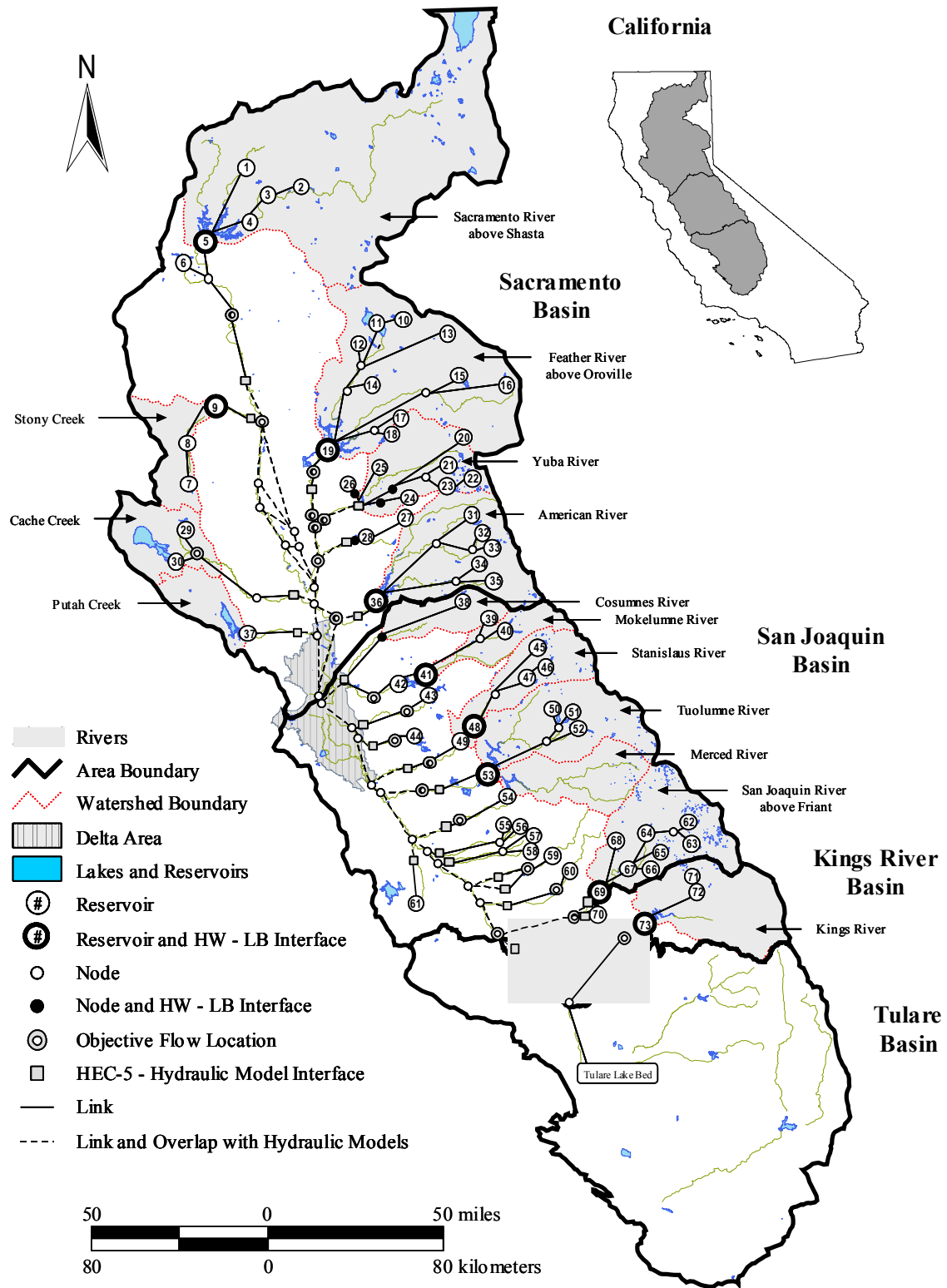


Figure 3: Translation of average natural flows (from frequency curves) to synthetic rain flood hydrographs. The 5-day pattern obtained from historic events is repeated to form a 30-day series.

Figure 4: Reservoir model schematic. Circles 1-73 highlight reservoir locations. Several watershed areas are delineated. For a listing of reservoir names and background information please refer to Hickey et al. (in press).



HEC-5 Methodology

Reservoirs were included based on two criteria: 1) existing flood damage reduction function or 2) active storage greater than 10,000 ac-ft and regulation of a significant natural drainage area. Most facilities modeled do not have formal flood damage reduction responsibilities, but all reservoirs alter the form and timing of flood hydrographs. The influence of non-flood damage reduction reservoirs is significant and cannot be ignored in a holistic watershed study.

Simulation models were developed for both the Sacramento and San Joaquin River Basins. Due to basin operations and the number of facilities and control points, these models were further split into headwater models and lower basin models. The headwater model for each basin generally contains reservoirs located upstream of flood damage reduction projects. Lower basin models contain those flood projects as well as a few water supply, recreation, and hydropower facilities.

A 3-step process was required to analyze each storm centering. First, headwaters models were simulated. Second, using the resulting storage time series for select headwater facilities, top of conservation storage for those flood damage reduction projects with established credit space agreements were computed. Finally, using results of the headwaters simulations and computed top of conservation series, the lower basin models were simulated. Full basin simulations were run for each centering regardless of storm location or intensity.

Headwaters (Step 1)

Headwater reservoirs are typically located in the watersheds above flood damage reduction projects. Primarily used for water supply and hydropower generation, these facilities do not have formal (Congressionally authorized) flood operations. A total of 46 headwater reservoirs were modeled, mostly in the Sacramento Basin (28 sites).

Operational Criteria and Physical Characteristics. Headwater reservoirs typically do not have scripted or published criteria to guide modelers. In this study, criteria were developed through conference calls with facility owners and operators and analysis of gage data. Elevation-capacity tables, outlet and spillway ratings, and facility schematics were obtained from the California State Division of Safety of Dams.

Preparing model input. Prior to simulation of headwater reservoirs, flows needed to be split from the single unregulated flow series at the hydrograph location (prepared in the Synthetic Hydrology) into inflows at all upstream reservoirs (figure 5). These flow splits were performed for each tributary by multiplying the full unregulated hydrograph by a constant percentage based on drainage area ratios, normal annual precipitation (NAP) distribution within the tributary basin, and volume comparisons of historical flood volume yields at the headwater reservoir and at the full unregulated flow location. In some instances, the volume comparison was not possible due to a lack of data and the ratio was based solely on NAP distribution and drainage areas.

Simulation product. Regulated flows at model interfaces (between headwater and lower basin models) continue in the simulation process as inflow data for the lower basin simulation models. Comparison of these computed regulated flows and their corresponding unregulated flows provides an excellent visual of the combined influence of headwater reservoirs for individual watersheds. These relationships are discussed for the Sacramento (at Shasta), American, Tuolumne, and San Joaquin (at Friant) Rivers in the results section of this paper.

Top of Conservation Storage (Step 2)

The required top of conservation storage is specified on the flood control diagram for each project. Typically, the top of conservation varies seasonally, as a function of basin wetness, and in some cases as a function of the concurrent storage of reservoirs upstream of the project.

The basin wetness parameter is a function of the total precipitation that has fallen over the watershed above the flood damage reduction reservoir in the rainy season to date. Since the reservoir models were prepared to simulate flood events and most major runoff events occur in wet years, computation of the top of conservation assumed that the basin wetness parameter would be high enough to reduce the top of conservation to the minimum level in all X% floods studied. Any seasonal variations along this minimum were included in the model script.

Top of conservation for projects with established credit space scenarios (where part of the required flood space in a flood damage reduction reservoir may be offset by space available at upstream reservoirs) were computed as an interim process between simulations of the headwater and lower basin models.

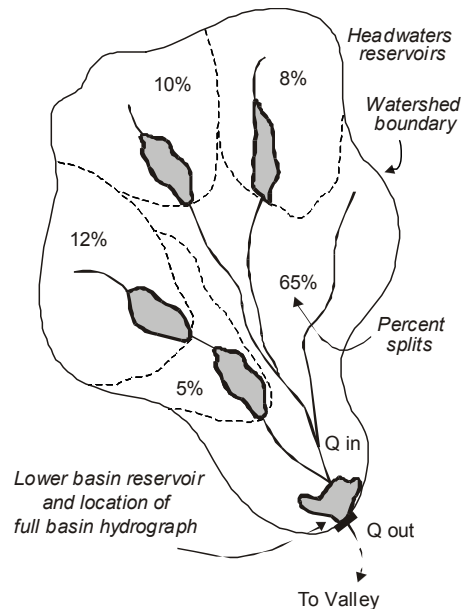


Figure 5: Splitting of a full unregulated hydrograph (generated in the Synthetic Hydrology) into inflows for headwater reservoirs.

Lower Basins (Step 3)

Twenty-four of the 27 lower basin reservoirs have storage dedicated to flood damage reduction. Eighteen of these reservoirs, all with flood storage, are located in the San Joaquin and Tulare Basins.

In accordance with the Flood Control Act, the USACE has established flood damage reduction operations for all reservoirs with flood space. These operations are described in Sacramento District-maintained Water Control Manuals and were incorporated into the models as directly as possible.

Model development focused on flood simulations where flood damage reduction reservoirs are encroached.

Physical Characteristics, Objective Flows, and Starting Storage. All required data (elevation-capacity tables, outlet and spillway ratings, facility schematics, and objective flows) were available in the Water Control Manuals. Starting storages were set at the top of conservation for all flood damage reduction projects. Reservoirs are operated to maintain flows at or below objective limits and will (if possible) curtail releases to accommodate tributary flows confluencing between the dam and the downstream locations.

River Routings. Muskingum routings, procedures which delay and attenuate flows as hydrographs travel downstream, were used for all river reaches in the lower basin models.

Local Flows. Local flows are unregulated tributaries that join with larger tributaries between reservoirs in series, between a flood damage reduction reservoir and its objective flow location, or downstream of objective flow locations. In this study, local flows were modeled in one of two ways. Hydrographs for local flows were either produced in the Synthetic Hydrology or were computed as a percentage of a nearby natural hydrograph. Percentages were estimated based on comparisons of short duration maxima (peak, 1-, and 3-day) for the local and nearby natural hydrographs. These local flows were input into the HEC-5 model and, in some cases, influenced reservoir outflows by filling part or all of the downstream allowable flows.

ESRD Simulation. Emergency Spillway Release Diagrams are formulated for reservoirs with gated spillways. Diagram operations trigger only in dire situations and may call for emergency releases above downstream limits before available flood and surcharge storage is exhausted. Each reservoir's ESRD is unique. Some base emergency releases on the rate the pool is rising, others as a function of the inflow. Diagrams often have ranges of pool elevations that specify the use of different sets of release criteria.

In this study, gated releases were modeled by entering certain characteristics directly (spillway width and pool elevations for spillway crest and surcharge levels) and adjusting the recession variable (allows HEC-5 to anticipate the total volume contained in a flood wave and compute releases to best pass that volume) until model results reflected ESRD operations as closely as possible.

Simulation Product. The lower basin simulation is the final step in translating X% unregulated hydrographs, produced in the Synthetic Hydrology, to regulated X% flows. In the Comprehensive Study modeling procedure, these results provide the hydrologic input for hydraulic models, which perform detailed routing of the flows through foothill and valley floor areas to delineate floodplains and generate stage-frequency information needed by economic modelers to estimate expected annual damages.

Model Calibration and Verification

Model calibration and verification was unique because the goal was not to reflect recorded history. Instead, modeling sought to portray "by the book" operations. As severe floods dictate event-specific operations, an ideal

validation data set does not exist. Therefore, modelers inspected simulation results to confirm agreement with operations under existing conditions for headwater and lower basin reservoirs.

Results and Discussion

This section consists of a series of short discussions detailing simulation results of 2 major tributaries in the Central Valley. Figures 6 and 7 plot sample flood simulations. Results for all tributaries are available in USACE and Rec Board (2000).

Figure 6: Simulation results for Don Pedro Reservoir (Tuolumne River tributary centering, 2% event).

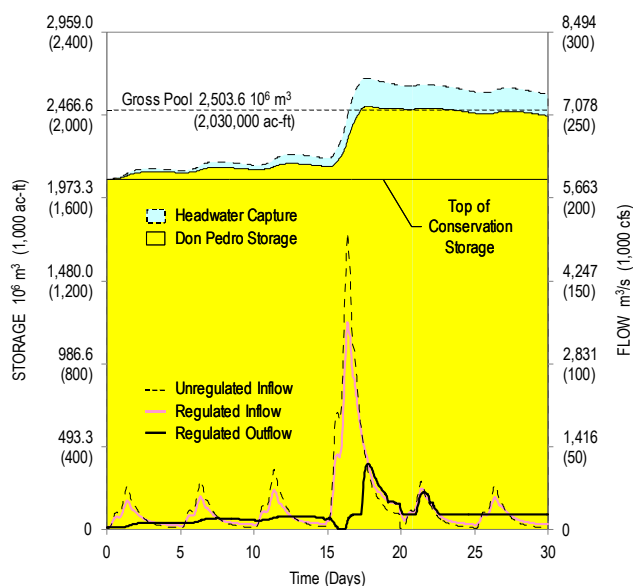
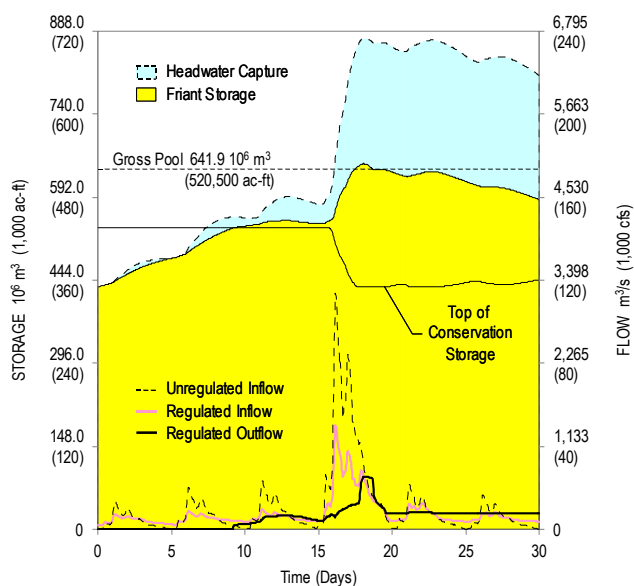


Figure 7: Simulation results for Friant Reservoir (San Joaquin River at Friant tributary centering, 2% event)



Note: Headwater capture is the combined storage in excess of starting storage for headwater reservoirs in the San Joaquin River Basin (above Friant) and is plotted on top of the Friant storage time series.

Tuolumne River

Headwaters. The 3 headwater reservoirs modeled above Don Pedro Reservoir are an important source of water for the City of San Francisco and are operated first for water supply and then for hydropower. Their combined gross pool storage is 630,000 ac-ft, of which 160,000 ac-ft is vacant at the start of the model simulations.

These reservoirs regulate 40 percent of the Tuolumne natural inflow to Don Pedro. The combined effects of these reservoirs reduced the peak inflow by an average of 23.9 percent and captured an average of 80,000 ac-ft during the critical 4%, 2%, and 1% simulations.

Lower Basin. Don Pedro Reservoir has 340,000 ac-ft of flood space and provides flood protection to downstream areas including the City of Modesto. At Modesto, Dry Creek, a local flow, joins the Tuolumne River. Don Pedro operates to maintain flows below the Dry Creek confluence within objective limits. Dry Creek's influence is visible in Don Pedro simulations when regulated outflows lower while storage and inflow are increasing (figure 6). Simulation results indicated that Don Pedro will spill in all events more severe than the 4% flood.

San Joaquin River (at Friant)

Headwaters. The Upper San Joaquin is among the most heavily regulated basins within the study area. Seven headwater reservoirs, which regulate 75 percent of the natural flow at Friant, were included in the model. Their combined gross pool storage is 590,000 ac-ft, of which 310,000 ac-ft is vacant at the start of model simulations.

The combination of number of facilities, available storage, methods of operation, spatial distribution, and percentage of natural flow regulated proved to be very influential in reshaping natural flood hydrographs at Friant. In fact, the hydrology in the Upper San Joaquin was more altered than that of any other headwater basin. Peak inflows were reduced by an average of 51.3 percent for all events and approximately 123,000 ac-ft was captured during the critical 4%, 2%, and 1% simulations.

Lower Basin. Friant Dam has 170,000 ac-ft of flood space. Friant operates for downstream locations below the Little Dry Creek confluence and at Mendota. Simulations perform very well for criteria below Little Dry Creek. This accuracy is not apparent for the Mendota location, which is located further downstream, below a large diversion and a confluence with another significant tributary. Like Don Pedro, simulation results indicated that Friant will spill in all events more severe than the 4% flood (figure 7).

Conclusions

To define baseline hydrologic conditions for the 50%, 10%, 4%, 2%, 1%, 0.5%, and 0.2% exceedance flood events, 23 storm centerings were developed. Hydrologic analyses performed for large spatial areas present challenges and opportunities unique to such ambitious studies. The Comprehensive Study has made possible a system-wide update for Central Valley unregulated rain flood hydrology and an overall modernization of the models used by Sacramento District hydrologists and engineers. These accomplishments will prove valuable to the Comprehensive Study and to future studies undertaken by public and private organizations.

The 73 reservoirs included in the model contain 25,600,000 ac-ft of storage at gross pool. The combined storage of all Central Valley reservoirs larger than 10,000 ac-ft is 26,100,000 ac-ft (not including the San Luis Reservoir Complex or facilities outside the study area). Therefore, 98 percent of all gross pool storage in the study area (in reservoirs larger than 10,000 ac-ft) is simulated with each full model run. To the knowledge of the authors

and of the Hydrologic Engineering Center, this report details the largest HEC-5 flood simulation model ever constructed.

Results of this study provide a good representation of without-project conditions and the models created will be valuable to further analysis of flood damage reduction alternatives in the Central Valley. Several conclusions follow:

- Large-scale watershed perspectives improve the overall quality of flood frequency analyses. Linking individual tributaries and system effects creates inherent checks and balances that can be used by engineers and hydrologists as quality management criteria.
- Use of generalized storms to simulate high water conditions in mainstem areas is very important to the consistent incorporation of hydrologic results into hydraulic and economic investigations. In many cases, violation of the storm centering guidelines would force hydraulic modelers into difficult and subjective decisions on how to delineate floodplain extent. Working within the “Composite Floodplain” framework prevents inconsistencies that would complicate ensuing analyses common to both planning studies and floodplain mapping.
- There seems to be a new emphasis in Congressional appropriations that favors large-scale watershed studies like the Sacramento and San Joaquin River Basins Comprehensive, the Upper Mississippi River Study, and the Central and South Florida (Everglades) Project. When studies such as these involve macroscale hydrologic and hydraulic analyses, the public would be better served if both the USACE and FEMA could utilize the technical products.

In the past, USACE and FEMA procedures for planning studies and regulatory floodplains have differed. Ultimately, project goals and stakeholder requirements will diverge sufficiently to prevent a single work from fulfilling the needs of both, but there is enough overlap in the early (and often most costly) phases to warrant coordinated technical development. To the authors’ knowledge, procedures documented in this manuscript are viable for hydrologic support of both regulatory floodplains and flood damage reduction studies. Perhaps Comprehensive Study concepts can fuel discussion regarding common methodologies.

- Modeling within the “Composite Floodplain” framework for hydrologic and hydraulic studies was elegant. Storm centerings provided an inherent archival system for model results and, since full basin simulations were run for each centering regardless of storm location or intensity, model adjustments between simulations were trivial. In fact, only the names of the input data needed to be changed when assessing a different storm centering.
- After viewing the multitude of Comprehensive Study flood simulations, it is difficult not to step back and consider the awesome regulating influence of reservoirs in California’s Central Valley. In the 2 simulation

excerpts presented, peak flows were reduced by an average of 78 percent. And these were events that exceeded the flood management capabilities of the tributary systems. Lesser floods simply flat-lined or did not approach allowable release limits.

As society has developed around this protection, it is difficult to foresee a future where the roles of reservoirs in flood damage reduction are greatly reduced. Instead, operations will need to deal with an increasing variety of demands, especially in the environmental arena where prescribed variability (i.e., experimental and, eventually, designed flooding) will one day become accepted operations for reservoirs controlling long downstream reaches with ecosystems that bear or could bear semblance to natural conditions.

- To date, this work has been well received by technical reviewers, public and private agencies, and the general public. Credibility has been enhanced through the exhaustive use of available historic data and by operating within the context of standard frequency analysis guidelines. These have been key to the ongoing acceptance of this large, high profile study.

Products of the hydrology and reservoir efforts feed ongoing hydraulic, economic, and ecosystem modeling. From supporting emergency operations with real-time modeling of river flows, floodplains, and damages, to the scientific study of controlled flooding designed to reestablish riparian habitats, the potential of this group of linked models is tremendous.

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